

RAI: Volume 3, Chapter 2.2.1.3.1, Third Set, Number 1:

Provide a technical basis for the assumption that empirical data from testing of Alloy 22 in basic saturated water is sufficient to establish the stress corrosion cracking (SCC) initiation criterion for waste packages that may contact a broader range of potential chemical/material conditions in the repository, including:

- Waste package in contact with seepage water brines (e.g. simulated concentrated water and simulated acidic water);
- Waste package in contact with deliquescent brines;
- Waste package in contact with aqueous chemical solution when there is sulfur accumulation at the metal-passive film interface or at grain boundaries.

Basis: DOE assumes that SCC in the waste package initiates when the residual tensile stress exceeds a threshold value given by a uniform distribution in the range of 90 to 105 percent of the at-temperature yield strength of Alloy 22 (SNL, 2007a, Table 6-3). DOE estimates the threshold tensile stress value by conducting constant-load crack-initiation tests on several Alloy 22 samples immersed in 15 percent basic saturated water at 105 °C. Although basic saturated water is one of the representative in-drift chemical solutions that could exist at the repository site, other potential brine solutions, such as simulated concentrated water and simulated acidic water, could also exist in the repository environment (e.g., SAR Table 2.3.6-1). Since DOE has not excluded SCC of Alloy 22 in dust deliquescence brines, the alloy may undergo SCC in dust deliquescence brines which may be considerably more aggressive than basic saturated water. In addition, compositions distinct from basic saturated water also can occur when there is sulfur accumulation at the metal-passive film interface, or at grain boundaries in the presence of an aqueous chemical solution (Jung et al., 2007).

DOE has not provided a technical basis to demonstrate that the use of basic saturated water appropriately represents the range of chemical environments that may occur on a waste package and potentially initiate SCC. The requested information is needed to demonstrate compliance with 10 CFR 63.114(f).

1. RESPONSE

Based upon constant load and slow strain rate tests performed in a wide variety of repository relevant brine compositions, bicarbonate containing brines such as simulated concentrated water (SCW) and 15% basic saturated water (BSW) have been identified as the most aggressive, repository-relevant brines in terms of their tendency to support stress corrosion cracking (SCC) of Alloy 22.

Alloy 22 is highly resistant to SCC due to the presence of a chromium-rich passive film formed in a wide range of environments, from oxidizing to reducing conditions, and at various pH values and temperatures (Jung et al. 2007, p. xii). However, SCC initiation is conservatively assumed to occur immediately in the total system performance assessment (TSPA), regardless of aqueous environment, if the surface tensile stress on the Alloy 22 waste package outer barrier (WPOB) exceeds the SCC initiation threshold stress criterion. The SCC initiation criterion of 90% to 105% of the at-temperature yield strength is based on long-term, constant load, tensile tests on Alloy 22 specimens exposed in aerated 105°C, 15% BSW brine (SAR Sections 2.3.6.5.2.1 and 2.3.6.5.3.2). 15% BSW brine is an aggressive solution compared to other repository-relevant solutions. Several additional corroborative tests have been performed which demonstrate the excellent resistance of Alloy 22 to SCC.

Regarding the seepage water brines, there is a very low probability (3.4×10^{-4}) that these waters will contact the WPOB prior to 10,000 years. At 10,000 years, the waste package surface temperature will be at or less than 30°C to 70°C for the full range of waste packages (see response to RAI: 3.2.2.1.2.1-4-005) (after 10,000 years the temperature decreases such that the new range has a low less than 30°C and a high less than 70°C). Further, as indicated in FEP 2.1.09.28.0A (SNL 2008), deliquescent brine volumes will be extremely limited (~1.8 $\mu\text{L}/\text{cm}^2$ at 120°C or higher), and their concentrations may also be diluted if condensation were to occur under the drip shields, drip onto the waste packages, and mix with the deliquescent brine layer.

With respect to the effect of sulfur on SCC initiation susceptibility, as discussed in the response to RAI: 3.2.2.1.3.1-2-005, the presence of relatively high molybdenum content (and chromium content) in Alloy 22 will mitigate any potential deleterious effect of sulfur.

1.1 JUSTIFICATION FOR USING 15% BSW SOLUTIONS FOR SCC THRESHOLD DETERMINATION

A series of slow strain rate tests revealed that the bicarbonate containing SCW brine was the most aggressive environment tested with respect to SCC initiation in Alloy 22. Chiang et al. (2005) found that bicarbonate ions act synergistically with chloride ions to promote transgranular SCC of Alloy 22 at high applied potentials. The composition of 15% BSW is approximately 0.76 M Cl^- , 0.43 M NO_3^- , 0.27 M CO_3^{2-} with lesser amounts of SO_4^{2-} , F^- , and SiO_3^{2-} (SNL 2007a, Section 6.2.1.1). The 15% BSW brine is similar to, but somewhat higher in chloride and lower in carbonate than, SCW brine which contains 0.5 m Cl^- + 1.1 m HCO_3^- . The composition of the diluted BSW brine used in the constant load tests (~15% BSW) was obtained by diluting full-strength BSW (composition ~ equivalent to fully evaporated J-13 well water, i.e., $\sim 50,000 \times$ J-13 (SNL 2007b, Section 6.6.4)). This resulted in measured pH values at 105°C of ~10.3 for the 15% BSW brine (SNL 2007a, Section 6.2.1.1), as compared to measured pH values for full strength BSW of ~12.2 to 12.3 at 100°C (Andresen et al. 2002, p. 6). The actual bicarbonate concentration in carbonate type brines is a strong function of the pH (Shukla et al. 2006, Figure 1; Chiang et al. 2006b, Figures 5-1, 5-2, and 5-3). For a closed system containing a 1 M NaCl brine at 95°C, the speciated concentrations of bicarbonate, carbonate, and carbonic acid are presented as a function of solution pH (Shukla et al. 2006, Figure 1). The bicarbonate concentration is a maximum at pH values of ~6 to 10 and drops by almost two orders of

magnitude when the pH increases from 10 to 12. Similarly, for open systems with various partial pressures of carbon dioxide, the bicarbonate concentration increases rapidly with increasing pH up to at least 10 (Chiang et al. 2006b). Thus, considering the accelerating effect of bicarbonate on SCC susceptibility of Alloy 22, the 15% BSW brine used in the constant load tests with a pH of ~10.3 is a relatively aggressive SCC initiation environment like SCW.

1.2 SUMMARY OF ALLOY 22 SCC INITIATION TEST RESULTS FOR A BROAD RANGE OF REPOSITORY-RELEVANT AND ACCELERATED ENVIRONMENTS

As described in SAR Section 2.3.6.5.2.1 and in more detail in *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials* (SNL 2007a, Section 6.2), SCC initiation has been evaluated using a variety of test techniques. These techniques included constant load tests (on “smooth surface” specimens and specimens containing simulated weld flaws), single and double U-bend tests, and slow strain rate tests (SSRTs) performed over a range of applied anodic potentials.

1.2.1 Constant Load Tests in Diluted 125°C and 105°C BSW Brine

Constant load, SCC initiation tests were performed on Alloy 22 specimens for an initial short time period (~2,000 hours) at 105°C to 125°C and a second longer time period of about four years duration at 105°C in an aerated BSW brine diluted to about 15% of full BSW concentration (SNL 2007a, Section 6.2.1.1; Andresen and Kim 2009, Figure 25). 15% Diluted BSW is a relatively aggressive SCC initiation environment. The specimens tested included a broad range of metallurgical conditions, such as mill annealed, as-welded, and thermally processed, to allow the formation of long-range ordering (LRO) or topologically close packed (TCP) phases and the cold worked condition. Specimens were tested in both the boldly exposed and tightly creviced conditions. A number of specimens also contained sharp notches (stress raisers). As described in *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials* (SNL 2007a, Section 6.2.2), the Alloy 22 SCC initiation threshold stress criterion of 90% to 105% of the at-temperature yield strength was based on constant load test results for exposure times of up to 3.2 years and at applied stresses of up to 203% of the at-temperature yield strength. Test time was subsequently extended to about 4 years without SCC initiation (Andresen and Kim 2009, Figure 25). The maximum threshold stress value was chosen to be about one-half the maximum applied test stress, similar to the stress reduction factor of one-half applied by the ASME code to the run-out stress for high cycle fatigue (SAR Section 2.3.6.5.4.2). Although the stress threshold criterion was based on the constant load test, it was determined to be conservative based on a range of corroborative tests as described in this response.

In addition to the constant load tensile tests, a series of SCC crack initiation tests are ongoing utilizing as-welded compact tension specimens (18 total) containing simulated sharp weld flaws, produced by fatigue pre-cracking, with the flaw tips in Alloy 22 weld metal. These specimens have been on-test in aerated 105°C, 15% BSW brine for over two years (e.g., 20,000 hours) at applied stress intensity factors as high as 33 MPa \sqrt{m} (Andresen and Kim 2009, Section 4). Changes in apparent crack length to date are nil for most specimens and very minor (<50 μm) for

three specimens. These small changes are likely the result of uncertainty in the measurement technique due to factors associated with the crack length measurement system as described by Andresen and Kim (2009, p. 4).

1.2.2 U-bend Tests in Long Term Corrosion Test Facility

A series of SCC initiation tests was performed on annealed and welded U-bend specimens exposed to a range of repository-relevant, aerated seepage type brines in the vapor and liquid phases at 60°C and 90°C (Fix et al. 2003). These concentrated J-13 well water-type brines included simulated dilute water (SDW) [pH ~10, ~10× J-13 well water], simulated acidified water (SAW) [pH ~3, ~1,000× J-13 well water], and SCW [pH ~10, ~1,000× J-13 well water]. The nominal compositions of these brines are listed in SAR Table 2.3.6-1. The initial stress on these U-bend specimens was somewhat over the 0.2% offset yield strength of Alloy 22 since the total apex strain was ~12% (SNL 2007a, Section 6.2.1.2.1). Periodic examinations of these specimens were performed after exposure times up to 5 years. Examinations were performed using a stereoscopic microscope at up to 100 times magnification. In addition, selected specimens were also examined using scanning electron microscopy and cross-sectional metallography. No evidence of SCC initiation has been observed to date.

1.2.3 Slow Strain Rate Tests with a Range of Applied Anodic Potentials

An SSRT involves pulling a tensile specimen immersed in the test environment to a continuously increasing strain, at a nominally constant strain rate, until the specimen ultimately fails. The failure time, load at failure, reduction in area at failure, and total elongation at failure, can be related to SCC initiation susceptibility. Although the slow strain rate test generally does not provide the actual stress at which initiation occurs, it is an effective test to evaluate the effect of the environment on susceptibility to SCC initiation in a relatively short time (ASM 1987, p. 260).

A series of SSRTs was performed for a broad range of potentially repository-relevant seepage and deliquescent type brines, as well as more aggressive environments, using anodic polarization as an additional accelerating factor. Selected results from the tests listed in SAR Table 2.3.6-14 and summarized in *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials* (SNL 2007a, Section 6.2.1.3) are listed in Table 1. Environments evaluated included SAW, SCW, and BSW seepage brines, and several potential deliquescent type brines, including simulated saturated water (SSW) (SAR Table 2.3.6-1) and 1 to 4 M NaCl and 8.5 M CaCl₂ brines. A summary of the potentially relevant test environments and associated test conditions selected are listed in Table 1 along with selected literature results. It is evident from Table 1 that the only relevant or accelerated environments in which SCC was observed are the bicarbonate containing brines such as SCW and 1 M NaF, but only when anodically polarized above the corrosion potential. Although incipient SCC was reported in 1 M NaF at 90°C and 400 mV applied potential, the failure load and time-to-failure of this specimen was similar to specimens with no SCC and tested at +400 mV in a range of other environments at similar temperatures. This indicates that the incipient cracking is likely to have initiated at stress levels near the ultimate tensile strength, which is consistent with a very low potential SCC initiation susceptibility.

For the much more SCC aggressive carbonate containing environments, Chiang et al. (2005) found that bicarbonate ions act synergistically with chloride ions to promote transgranular SCC of Alloy 22 at applied potentials above the corrosion potential as indicated by the results listed in Table 1. For SCW containing 0.2 M Cl^- and about 1.1 M HCO_3^- (Chiang et al. 2005), the transition from no cracking to SCC occurs between about 200 and 400 mV_{SCE} (where SCE is the saturated calomel electrode). The susceptibility in SCW at a given applied potential decreases with temperature with no SCC observed at room temperature. As indicated in Table 1, using results from Chiang et al. (2006a, Table 4), for a 1.1 M bicarbonate solution containing a more concentrated chloride level (7.2 M Cl^-), the transition occurs between 100 and 200 mV_{SCE}. Chiang et al. (2005) also found that for concentrated chloride brines (e.g., 7.6 M NaCl + 0.38 M NaNO₃) without bicarbonate, similar to some deliquescent brines, no SCC is observed, even at applied anodic potentials as high as 400 mV at 95°C.

The application of anodic potentials as high as 400 mV_{SCE} can approximate the corrosion potentials achieved in deliquescent type brines at lower pH values and/or much higher nitrate levels, which can be as high as ~500 to 600 mV versus SSC (saturated silver/silver chloride electrode) at higher temperatures (Lian et al. 2007). Deliquescent type brines may raise the Alloy 22 corrosion potential above E_{SCC} , which has been suggested as a SCC crack initiation criterion, at least for bicarbonate-containing brines (Chiang et al. 2006b, Section 5.2). Based on the observations in the SSRTs, that SCW is one of the more SCC aggressive environments evaluated, a subsequent series of U-bend SCC crack initiation tests at 165°C and crack growth rate tests at 150°C using pre-cracked compact tension specimens are underway in aerated SCW brine.

Two highly-instrumented slow strain rate SCC crack initiation stress tests were performed in SCW (Fix et al. 2003). Test conditions for these two specimens were 86°C at an applied potential of 400 mV_{SSC} and 89°C at an applied potential of 200 mV_{SSC}. Crack initiation did not occur until the last stages of straining (at the high stress of 605 MPa and above), when the applied stress reached levels near the ultimate tensile strength. The reported room temperature yield strength for these Alloy 22 specimens is ~380 MPa, indicating that SCC did not initiate in these tests until well above the at-temperature yield strength since it is lower than the room temperature yield strength.

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Table 1. Summary of Slow Strain Rate Test and Other SCC Initiation Test Results for Alloy 22 in a Range of Environments

Slow Strain Rate Tests						
Test Environment	pH at Room Temperature	Temperature (°C)	E_{corr} mV*	$E_{applied}$ mV*	SCC	Ref.
1 M NaCl	6.9	90	-104	+400	No	a
4 M NaCl	6.2	98	-323	+349	No	a
7.2 m Cl ⁻	7.0	95	—	+400	No	c
8.5 M CaCl ₂	~6	120	-140 to -180	E_{corr}	No	a
1 M NaF	7.6	90	-244	+400	Incipient SCC	a
3.8 M NaCl + 0.38 M NaNO ₃	9.8	95	—	+400	No	b
SSW (3.6 M Cl ⁻ and 21.2 M NO ₃ ⁻)	~6	100	-154	+400	No	a
7.6 M NaCl + 0.38 M NaNO ₃	7.0	95	—	+400	No	b
SAW	~3	63	-7 to +360	E_{corr}	No	a
SAW + 0.005% Pb(NO ₃) ₂	~3	95	-90 to +400	E_{corr}	No	a
BSW	~13	105	-323	+400	No	a
SCW (0.19 M Cl ⁻ + 1.1 M HCO ₃ ⁻)	~9 to 10	90	-143	E_{corr}	No	a
SCW (0.19 M Cl ⁻ + 1.1 M HCO ₃ ⁻)	~9 to 10	86	-169	+400	Yes	a
[Cl ⁻] + [HCO ₃ ⁻] as in SCW	8.7	95	—	+400	Yes	b, c
0.5 m Cl ⁻ + 1.1 m HCO ₃ ⁻	8.8	95	—	+400	Yes	b
15% BSW (0.76 M Cl ⁻ , 0.43 M NO ₃ ⁻ , 0.27 M CO ₃ ²⁻)	10.3 (at 105°C)	105	—	E_{corr}	No**	f
7.2 m Cl ⁻ + 1.1 m HCO ₃ ⁻	8.7	95	—	+300	Yes	c
7.2 m Cl ⁻ + 1.1 m HCO ₃ ⁻	8.5	95	—	+200	Yes	c
7.2 m Cl ⁻ + 1.1 m HCO ₃ ⁻	8.6	95	—	+100	No	c
Other Selected Alloy 22 SCC Initiation Test Results from Literature						
45% MgCl ₂ (6-week U-bend test)		154			No	d
14 m Cl ⁻ (as MgCl ₂). Fracture mechanics test at 32.7 MPa/m for 52 weeks		110	-280 to -250	E_{corr}	No	e
9.1 m LiCl. Fracture mechanics test at 47 MPa/m for 21 weeks		95		-250	No	e

Sources: ^aSAR Table 2.3.6-14 (strain rate = $1.66 \times 10^{-6} \text{ s}^{-1}$).^bChiang et al. 2005, Table 4 (strain rate ~ $3.2 \times 10^{-6} \text{ s}^{-1}$).^cChiang et al. 2006a, Table 4.^dFix et al. 2003.^ePan et al. 2002.^fAndresen et al. 2002, Table 2-1, Section 2.3.* $E_{applied}$ reported relative to the SSC (saturated silver/silver chloride) for references a and d and relative to the SCE (saturated calomel electrode) for references b, c, and e.

**Constant load test, not slow strain rate test.

1.2.4 Single and Double U-bend Specimens Exposed to 165°C Aerated SCW Brine

A range of metallurgical conditions have been evaluated as single and double U-bend specimens, including material heat treated to produce long range ordering and topologically close packed phases, thereby rendering the material more susceptible to localized corrosion phenomena. A series of single (16 specimens) and double (10 creviced specimens) U-bend specimen tests in 165°C aerated SCW brine has been underway for over 32,000 hours (~3.7 years) with no evidence of SCC initiation (Andresen and Kim 2009, Table 1). The double U-bend specimens were fabricated from mill annealed material and the single U-bend specimens were machined from as-welded Alloy 22 plate with the weld positioned at the specimen apex. These U-bend specimens have been examined periodically and the loading bolts retightened periodically to compensate for potential stress relaxation that might occur at 165°C over long exposure periods (Andresen and Kim 2009, Table 2; Andresen et al. 2005, p. 3 and Table 5b). Thus, these U-bend specimens are likely to retain maximum tensile stresses near the apex region that are at or somewhat over yield strength levels consistent with being at or over the SCC initiation threshold stress level. Despite having a microstructure known to be more susceptible to localized corrosion phenomena, and being evaluated in an aggressive bicarbonate containing brine, SCC was still not observed.

1.2.5 Crack Growth Rate Tests in 150°C Aerated SCW Brine versus Air

A series of Alloy 22 crack growth rate tests on fatigue pre-cracked compact tension specimens was performed in 150°C aerated SCW brine along with companion specimens tested in 150°C air under the identical loading and cycling sequences. Very similar crack growth rates were measured for both cases, (i.e., air and brine). For example, Andresen and Kim (2009, Figures 3, 6, 9, and 12) provide a basis for comparison of crack growth rates (for about one-hour hold times at the maximum stress intensity factor (K_I) of 40 MPa \sqrt{m}) for specimens loaded in brine versus those loaded in air. After about 4,000 hours exposure under identical but varying loading conditions, the growth rates measured on two specimens exposed to the brine were 10^{-9} and 2.5×10^{-9} mm/s with an average rate of 1.7×10^{-9} mm/s. The corresponding growth rates in air were 3.9×10^{-9} and 3.4×10^{-9} mm/s which averages to 3.65×10^{-9} mm/s, about 2 times faster in air. The most likely reason for the somewhat higher growth rates in air is that less oxide forms in the crack wake, and therefore there is no crack closure from the presence of the oxide, leading to a somewhat higher effective stress intensity factor (Andresen and Kim 2009). However, the presence of similar growth rates in 150°C SCW and in air is indicative of little, if any, environmental effect on crack growth under these accelerated slow cyclic loading conditions under open circuit conditions.

1.3 POTENTIAL EFFECTS OF SULFUR ACCUMULATION AT METAL/PASSIVE FILM INTERFACE OR AT GRAIN BOUNDARIES

Anodic sulfur segregation can potentially occur during very long-term exposure under passive corrosion conditions. As discussed in the response to RAI: 3.2.2.1.3.1-2-005, the presence of molybdenum in Alloy 22 counteracts any potential deleterious effect of anodically driven sulfur segregation in that it forms bonds with sulfur (either adsorbed sulfur or sulfur exposed at sites of passive film breakdown), and the resulting molybdenum sulfide then dissolves under

repository-type oxic environmental conditions. In addition to the beneficial role of molybdenum, the high chromium content in Alloy 22 will result in the formation of a highly protective chromium oxide passive film, which will tend to effectively cover over any surface sulfide “islands” that might remain on the metal surface. If sulfur were to segregate to grain boundaries in the Alloy 22 matrix at the intersection of the grain boundaries with the metal surface, the same situation will prevail (i.e., sulfur will tend to form soluble molybdenum sulfides and/or remain covered by the highly stable chromium oxide passive film). Consequently, sulfur accumulation at the metal-passive film interface, or at grain boundaries, in the presence of an aqueous environment will not have a detrimental effect on potential SCC initiation in Alloy 22.

1.4 SUMMARY AND CONCLUSIONS

Based on an extensive series of slow strain rate SCC initiation tests performed by DOE and others, the 15% BSW brine is an aggressive solution for SCC initiation compared to other repository-relevant environments. Stress corrosion cracking initiation is conservatively assumed to occur in the TSPA, regardless of aqueous environment, if the surface tensile stress on the Alloy 22 WPOB exceeds the SCC initiation threshold stress criterion values, 90% to 105% of the at-temperature yield strength. The SCC initiation criterion is based on long-term constant load tensile tests on Alloy 22 specimens exposed in aerated 105°C 15% BSW brine. The test brine (BSW) is a bicarbonate-containing chloride brine with an at-temperature pH value of ~10.3. In addition to the constant load tests used to establish the SCC initiation criterion, Alloy 22 has been tested in the SCC supporting SCW environment for long times (~ 4 years) at temperatures up to 165°C with no SCC initiation observed. Furthermore, SSRTs have been performed in a wide range of non-bicarbonate containing chloride plus nitrate type brines more typical of deliquescent brines with no evidence of SCC initiation, even at high applied anodic potentials.

There is a very low probability (3.4×10^{-4}) that seepage brines will contact the WPOB prior to 10,000 years when the waste package surface temperature will be at or less than 30°C to 70°C for the full range of waste packages (see response to RAI: 3.2.2.1.2.1-4-005). Further, as indicated in FEP 2.1.09.28.0A (SNL 2008), deliquescent brine volumes will be extremely limited (~1.8 $\mu\text{L}/\text{cm}^2$ at 120°C or higher) and their concentrations may be diluted if condensation were to occur under the drip shields, drip onto the waste packages, and mix with the deliquescent brine layer.

With respect to the effect of sulfur on SCC initiation susceptibility, as discussed in the response to RAI: 3.2.2.1.3.1-2-005, the presence of relatively high molybdenum content (and chromium content) in Alloy 22 will mitigate any potential deleterious effect of sulfur.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

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NOTE: ^aProvided as an enclosure to letter from Williams to Sulima dtd 03/04/2009. "Yucca Mountain – Request for Additional Information – Safety Evaluation Report, Volume 3, Chapter 2.2.1.2.1 (Scenario Analysis), Third Set (Department of Energy's Safety Analysis Report Section 2.2, Table 2.2-5)."

RAI: Volume 3, Chapter 2.2.1.3.1, Third Set, Number 2:

Provide additional technical basis for the assumption that 50 μm is an appropriate depth for incipient stress corrosion cracks in the waste package.

Basis: DOE assumes that stress corrosion cracks could initiate at incipient flaws on a smooth surface when the residual stress is greater than the residual stress threshold (RST). DOE assumes that the depth of cracks that nucleate at incipient flaws is 50 μm at the time of initiation (SAR Section 2.3.6.5.2.2). DOE states that 50 μm is appropriate because it is based on the observation of SCC in nuclear reactor components by Ford and Andresen (1988) and because this depth is greater than the size of initiating cracks stated in NUREG/CR-5864 (Harris et al., 1992), which is 0.001 inch (25.4 μm).

DOE has not provided sufficient information to support the assumption that the crack initiation size in the waste package will be the same as that in nuclear reactor components. The incipient crack depths stated in the cited references are not based on mechanistic understanding of crack initiation, but are based on empirical observations of SCC in nuclear reactor components. Mechanistically, incipient crack size depends upon fundamental characteristics such as material composition, microstructure, type and size of flaws and defects in the material, and chemical environment, among others. Many of these characteristics differ between nuclear reactor components and the waste package. As such, nuclear reactor components may provide limited information regarding the nature of SCC in waste packages unless it is established that the parameters that affect crack size are, in both cases, similar. The requested information is needed to verify compliance with 10 CFR 63.21(c)(15) and 63.114(b).

1. RESPONSE

The incipient crack size does not affect the model treatment of stress corrosion cracking (SCC) initiation on the waste package outer corrosion barrier. It is conservatively assumed in the model that SCC initiates immediately in the form of 50-micron incipient cracks once the outer surface stress exceeds the initiation threshold stress criterion.

SCC (or environmentally assisted cracking) has historically been separated into “initiation” and “propagation” phases (SNL 2007a, Section 6.3.3). The particular crack size defining the boundary between the two phases is somewhat arbitrary. For the purpose of modeling initiation on smooth surfaces, an initiation crack size to account for microscopic crack formation at defect sites (e.g., precipitates, grain boundaries, and mechanical flaws) is assumed. The total system performance analysis (TSPA) uses an incipient crack size of 50 microns, as developed by Ford and Andresen (1988, p. 798) and Andresen (1991, Figures 39 to 41). Thereafter, the crack may either reach the arrest state or, if the crack tip stress intensity factor exceeds the threshold K_{ISCC} value, enter the “propagation” phase.

As discussed above and referenced in *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials* (SNL 2007a, Section 6.3.3), this incipient crack size is based on evidence presented in the open literature. Andresen (1991) describes a series of on-line measurements of crack extension versus exposure time obtained on compact tension specimens containing wet ground notches. The specimens (stainless steel, Alloy 600, and Alloy 182) were loaded to a stress intensity factor of 33 MPa \sqrt{m} and exposed to high-temperature aerated water environments containing sulfuric acid additions. From this set of measurements, it is evident in the work by Andresen (1991, Figures 39 to 41) that the slope of the crack extension versus time plots (i.e., the crack growth rate) increases very slowly over time until the crack depth reaches approximately 50 microns. At an approximately 50-micron crack depth, the crack growth rate quickly transitions to a much more rapid, relatively steady state value. Andresen (1991) attributed this change from very slow crack extension (initiation) to stable crack growth to the coalescence of individual microcracks and the establishment of a stable crack tip chemistry. Although the environments and alloys evaluated may differ, this concept is equally applicable to the Alloy 22 waste package outer barrier (WPOB) under repository type environmental conditions as it is to nuclear reactor components. For both cases, the austenitic-phase alloys undergo similar melting, fabrication, welding, and nondestructive evaluation processes. Consequently, the WPOB and nuclear reactor components, such as large diameter piping, would be expected to have similar metallurgical characteristics (e.g., microstructure, type and size of flaws, inclusion size and density, etc.). From the TSPA film rupture/slip dissolution model perspective, the protective passive film is chromium oxide for each of these alloys, as well as for Alloy 22, although the long-term passive film stability may vary among alloys due to differences in alloy additions such as molybdenum (Jung et al. 2007, Section 3.1).

The incipient crack size of 25.4 microns from NUREG/CR-5864 (Harris et al. 1992, p. 3-8) was a value selected as an input for performing a series of crack growth rate analyses to compare with reactor SCC experiences. In NUREG/CR-5864 (Harris et al. 1992, p. 3-8) it is stated that, "The depth of initiating cracks is taken to be 10^{-3} inch" and as such, it was not a mechanistically based value.

Even if the incipient crack size were to vary with material, the selection of a given size (e.g., 50 microns) does not affect the modeling of SCC crack initiation on the WPOB as it is conservatively assumed that SCC initiates immediately once the outer surface stress exceeds the initiation threshold stress criterion. Under nominal conditions, the subsequent crack growth rate is then driven by the through-wall stress intensity factor distribution, such as that shown in *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials* (SNL 2007a, Figure 6-58), for the residual stress mitigated (low plasticity-burnished), waste package outer lid final closure weld. In the case of seismic damage, if the resulting outer surface stress exceeds the threshold stress criterion, a network of through-wall stress corrosion cracks is considered to immediately form (SNL 2007b, Section 6.2.1). Consequently, the selection of an incipient flaw size does not affect waste package TSPA performance.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

Andresen, P.L. 1991. "Fracture Mechanics Data and Modeling of Environmental Cracking of Nickel-Base Alloys in High Temperature Water." *Corrosion 91*, The NACE Annual Conference and Corrosion Show, March 11-15, 1991, Cincinnati, Ohio. Paper No. 44. Houston, Texas: National Association of Corrosion Engineers.

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SNL (Sandia National Laboratories) 2007a. *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials*. ANL-EBS-MD-000005 REV 04 ERD 2. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070913.0001; LLR.20080311.0084; LLR.20080408.0242.

SNL 2007b. *Mechanical Assessment of Degraded Waste Packages and Drip Shields Subject to Vibratory Ground Motion*. MDL-WIS-AC-000001 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070917.0006; DOC.20080623.0002; DOC.20081021.0001.

RAI: Volume 3, Chapter 2.2.1.3.1, Third Set, Number 3:

Provide a technical basis for not considering waste package plate thinning in calculating the number of stress corrosion cracks per patch in the nominal scenario class.

Basis: DOE considers only six through-wall stress corrosion cracks per patch in the TSPA-LA model under the nominal scenario class. DOE states that separation distance between two through-wall cracks should be equal to, or more than, plate thickness. The initial crack separation distance is equal to the thickness of an emplaced waste package plate (25 mm). Based on a patch size of 150 mm x 150 mm, and thickness of 25 mm a maximum of six through-wall cracks could form on a single patch (SNL, 2008, Section 6.3.5.1.2). A plate thinned by general corrosion, however, would require less distance between through-wall cracks than a full-thickness plate. As such, more than six through-wall cracks could be possible on a 150 mm x 150 mm patch that is thinned by the general corrosion.

The crack area model indicates that crack area decreases as the waste package plate thins in the nominal case scenario (SNL, 2007a, Section 6.6.2). If only 6 cracks per patch are considered, the through-wall crack area would decrease in proportion to the square of the thickness of the plate as the plate thins in the nominal scenario class. The through-wall crack area density will approach zero as the thickness of the plate tends to zero. The requested information is needed to verify compliance with 10 CFR 63.114(f).

1. RESPONSE

In the event that through-wall cracks are formed due to stress corrosion cracking (SCC), the effective cross-sectional area of such through-wall cracks is represented within the total system performance assessment (TSPA) model as a pathway for diffusive transport of radionuclides out of the waste package (SAR Section 2.3.7). If the reduction in thickness of the waste package over time was considered in determining this cross-sectional area, there would be an increase in the number density of such cracks; however, this would result in only an insignificant change in the cross-sectional area of the waste package outer barrier breached via SCC cracks, and thus would have a negligible impact on the calculated rate of radionuclide release. Furthermore, the effects of initiation of inside out corrosion and waste package internal degradation within the TSPA (SAR Sections 2.4.2.2.1.1.2 and 2.4.2.2.3.2.2) are independent of the number of cracks, and thus are unaffected by waste package thinning.

1.1 SCC CRACK DENSITY AND GEOMETRY FOR THE BASELINE NOMINAL CASE VERSUS THE NOMINAL CASE WITH THINNED PACKAGES

In the TSPA analysis, when determining the crack density and crack opening displacement, the wall thickness is assumed to be equal to the initial thickness, and not thinned due to general corrosion. (SNL 2007b, Section 6.3.3.2.2).

However, the waste package outer barrier will thin over time due to general corrosion. As illustrated in SAR Figure 2.4-23, the degree of thinning will be very small in most cases. For 95% of realizations, general corrosion will result in a reduction of average thickness of less than 5 mm, with the waste package outer barrier remaining more than 20 mm in thickness, over a time period of one million years. If SCC cracks were to initiate and propagate through a 20-mm-thick outer barrier, the number of possible cracks per patch would increase from six to eight (i.e., the minimum spacing between through-wall cracks is equal to the thickness of the plate, so reducing the thickness means a higher number can fit in a given area).

In addition to the number density of cracks changing with thickness, the area per crack would also change. As discussed in *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials* (SNL 2007a, Section 6.3.5), a through-wall stress corrosion crack is assumed to be semicircular in nature, with a depth of a , and a length of $2c$. Since the crack is semicircular, $a = c$. The crack opening displacement, δ , for such a crack in an infinite sheet is defined as (Tada 2000, p. 125):

$$\delta = \frac{(4c)\sigma}{E} \quad (\text{Eq. 1})$$

Where σ is the stress and E is the Modulus of Elasticity. The opening of such a crack is elliptical in shape, with a short axis (crack width) equal to δ and the long axis equal to the crack length ($2c$). The cross-sectional area of the opening can be estimated as (SNL 2007a, Equation 31):

$$A_{cr} = \frac{\pi}{4} \delta (2c) = \frac{(2\pi c^2)\sigma}{E} \quad (\text{Eq. 2})$$

For a semicircular through-wall crack, c is equal to the thickness of the plate, t , and thus the equation above can be re-written as:

$$A_{cr} = \frac{\pi}{4} \delta (2t) = \frac{(2\pi t^2)\sigma}{E} \quad (\text{Eq. 3})$$

Assuming that the geometry and stress field scales with the thickness of the plate, the opening area for a given crack for the thinned case (i.e., $t = 20$ mm) can be compared with the nominal case (i.e., $t = 25$ mm), to yield the relationship:

$$\frac{A_{SCC}^{Thinned}}{A_{SCC}^{Nominal}} = \frac{t_{Thinned}^2}{t_{Nominal}^2} = \frac{(20\text{ mm})^2}{(25\text{ mm})^2} = 0.64 \quad (\text{Eq. 4})$$

Thus, the area per crack for the thinned case would be 36% less than that for the nominal case, and increasing the number of cracks per patch from six to eight would result in a net reduction in SCC crack area of 15%.

If, however, the crack length is assumed to remain constant as the plate thins, then the SCC crack area per crack would remain constant. As a result, increasing the number of cracks would result

in a proportional increase the total area of SCC cracks available to support diffusive mass transport. In this case, increasing from six to eight cracks would increase the cross-sectional area by 33%.

It should be noted, though, that increasing the number density of parallel through-wall cracks is not physically possible if the array of through-thickness cracks has already formed as the minimum spacing between two parallel through-thickness cracks is equal to the thickness of the plate. To insert additional through-thickness cracks requires that the spacing of all of the cracks be changed. In other words, if an array of six cracks were to initiate when the waste package outer barrier was at the initial thickness, it would not be possible to “insert” a parallel through-wall crack between two of the existing cracks, as the stress would be insufficient to drive a crack through the wall, as discussed in *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials* (SNL 2007a, Section 6.6.1).

1.2 RELATIVE CONTRIBUTION OF SCC CRACKS FORMED UNDER THE NOMINAL CASE TO THE FRACTION OF SURFACE AREA BREACHED BY SEISMIC-INDUCED CRACKS

The effects on repository performance of SCC cracking are estimated by the seismic ground motion modeling case for 1,000,000 years postclosure, which simulates the combined effects of seismic ground motion events and nominal processes. During the first 50,000 years, failure of waste packages by stress corrosion cracking due to nominal processes is rare (SAR Figures 2.1-13(b) and 2.1-15(b)) and makes negligible contributions to total mean dose. From about 50,000 years until 900,000 years postclosure, the igneous intrusion modeling case is the primary contributor to total mean dose to the reasonably maximally exposed individual (RMEI) (see SAR Figure 2.4-18(b)). Finally, after about 900,000 years postclosure, the seismic ground motion modeling case becomes the primary contributor to total mean dose to the RMEI.

In the seismic ground motion modeling case, which includes nominal corrosion processes (SAR Section 2.4.1.2.4), through-wall SCC cracks may form due to general corrosion and subsequent nominal stress corrosion cracking in the waste package outer barrier closure weld region or as a consequence of a seismic event. The total area of all SCC cracks is used in the models for transport of radionuclides from failed waste packages.

Seismic damage to waste packages is not observed in all realizations. When seismic damage occurs, the area of SCC cracks due to the seismic damage is far larger than the area of SCC cracks due to nominal processes, as shown in SAR Figure 2.1-13 for commercial spent nuclear fuel waste packages, and SAR Figure 2.1-15 for codisposal waste packages. Thus, in realizations where seismic damage occurs, an increase of 33% in the part of total crack area attributed to nominal processes would have a negligible effect on the mean of the total mean dose to the RMEI.

When seismic damage does not occur, waste packages remain intact until either: (1) general corrosion processes thin the outer barrier sufficiently such that incipient cracks initiate and propagate through the remaining outer barrier thickness, or (2) stress corrosion cracks associated with closure weld flaws penetrate the waste package outer barrier (SAR Section 2.1.2.2). Waste

package thinning is accounted for in the models that determine the time at which incipient cracks initiate. Thus, the only other effect of accounting for waste package thinning is to potentially increase or decrease the number and total area of stress corrosion cracks per patch.

When waste packages fail by SCC cracking, adsorbed water interior to the waste package creates pathways for radionuclides to diffuse through the waste package and the waste package outer barrier. Because the relative humidity in the waste package is taken to be equal to that exterior to the waste package, increasing crack area has no effect on the volume of water adsorbed. Radionuclides such as ^{99}Tc and ^{129}I , which are not constrained by solubility limits and do not sorb onto waste package corrosion products, are rapidly mobilized as the waste forms degrade and are readily transported from the waste package. Transport of these radionuclides is limited by the degradation processes of the waste forms and by the characteristics of the diffusive pathways (including SCC crack area).

In contrast, transport of other radionuclides, such as ^{242}Pu and ^{237}Np , which are constrained by solubility limits and which sorb onto waste package corrosion products, is inhibited by the low volume of water available interior to the waste package. These effects are manifested in the relatively low contribution of such radionuclides to the mean dose to the RMEI in the seismic ground motion modeling case (SAR Figure 2.4-26(b)), where ^{242}Pu and ^{237}Np contribute little to the mean dose until very late times, in contrast to ^{99}Tc and ^{129}I , which largely comprise the mean dose to the RMEI. The increased contribution from ^{242}Pu and ^{237}Np at late times results from the onset of advective flow through the waste packages, which occurs after general corrosion opens patches on the waste package outer barrier.

Thus, an increase of 33% in SCC crack area may increase the rate of transport of highly mobile radionuclides (such as ^{99}Tc and ^{129}I) from the waste package (SNL 2008, Figure 7.3.2-9) and cause a concomitant increase in mean dose to the RMEI, but only until the inventory of such radionuclides are depleted. Thereafter, the increased SCC crack area would have little to no effect on radionuclide releases. Thus, the effect on total mean dose to the RMEI would be at most an increase of 33% in the contribution from the seismic ground motion modeling case, for the period of time before advective flow through the waste packages becomes the dominant release mechanism (i.e., prior to 900,000 years postclosure). Because the igneous intrusion modeling case is the dominant contributor to the total mean dose to the RMEI prior to 900,000 years, a modest increase of 33% in the contribution from the seismic ground motion modeling case would result in at most a negligible increase to the total mean dose to the RMEI.

1.3 SUMMARY

Although considering the reduction in thickness of the waste package wall over time could increase the possible number density of cracks, this would result in an insignificant change in the cross-sectional area of the waste package outer barrier breached via SCC cracks, and thus would have a negligible impact on the calculated rate of radionuclide release. The net change in cross-sectional area breached via SCC cracks formed in the nominal scenario represents a very small fraction of the total area breached, as SCC cracks formed due to the seismic scenario dominate. Therefore, waste package plate thinning was not considered by the TSPA in calculating the number of stress corrosion cracks per patch in the nominal scenario class.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

SNL (Sandia National Laboratories) 2007a. *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials*. ANL-EBS-MD-000005 REV 04 ERD 2. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070913.0001; LLR.20080311.0084; LLR.20080408.0242.

SNL 2007b. *EBS Radionuclide Transport Abstraction*. ANL-WIS-PA-000001 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20071004.0001; LLR.20080414.0023.

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Tada, H., Paris, P.C., Irwin, G.R. 2000. *The Stress Analysis of Cracks Handbook*. 3rd Edition, New York, New York: McGraw-Hill.

RAI: Volume 3, Chapter 2.2.1.3.1, Third Set, Number 4:

Provide a technical basis for considering only the residual stress, and not the transient stress during and shortly after impact, in the model abstraction used to calculate the stress corrosion crack size (opening length and opening width) and crack density in the seismically damaged area of the waste package.

Basis: Mechanistically, SCC is typically considered as a three stage process: initiation, propagation, and arrest. DOE, however, uses a non-mechanistic model abstraction for SCC in the seismically-damaged area of the waste package. DOE assumes that through-wall cracks immediately form in areas where the residual stress is greater than the residual stress threshold, which is in the range of 90 to 105% of the Alloy 22 yield stress (SAR Subsection 2.3.4.5.1.2.1). Thus, in the DOE model, stress corrosion crack opening width and opening area depend upon the magnitude of the residual stress (Equations 33 and 34 in SNL, 2007).

Transient stresses during and shortly after impact, however, are higher than the residual stress. The transient stress may affect the size and density of defects in the damaged area, which may in turn affect the size of density of through-wall cracks. DOE has not provided a clear technical basis to support the assumption that such transient stresses do not need to be considered in the model abstraction for SCC in the waste package. The requested information is needed to verify compliance with 10 CFR 63.114(f).

1. RESPONSE

Due to the very short time period over which transient stresses are present, they will have no impact on the potential for, growth rate of, or resulting crack geometry for stress corrosion cracking (SCC) cracks. As such, transient stresses are not considered by the total system performance assessment (TSPA) in determining whether SCC can or cannot take place.

1.1 STRESS CORROSION CRACKING INITIATION CRITERIA

SCC describes relatively slow, environmentally assisted cracking, the propagation of which is the result of the combined and synergistic interaction of mechanical stress and corrosion reactions (ASM 2003, p. 346).

As discussed in SAR Section 2.3.4.5.1.2.1 and in more detail in *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials* (SNL 2007), the treatment of SCC in the TSPA conservatively assumes it will occur whenever the residual stress at a location within the waste package outer barrier exceeds the residual stress threshold (RST), regardless of the environment that exists at the waste package surface. During the postclosure period of performance, the waste package may be subjected to mechanical impact due to seismic events. If sufficient impacts occur, the high residual tensile stress resulting from such an impact may cause SCC. Note that the TSPA conservatively uses RST as the sole threshold criterion for SCC formation. The effect of environment, a critical aspect of scenarios where SCC is possible, is not

considered here. In other words, regardless of whether the waste package is dry or in contact with seepage water, or whether there is a defect to act as an initiation site, SCC is assumed to take place whenever the residual stress exceeds the RST.

Furthermore, for the seismic scenario, the stress corrosion cracks are assumed to propagate instantaneously. The use of a non-mechanistic approach is a conservative failure criterion because detailed corrosion models will have a delay time until failure (i.e., the corrosion aspect of SCC is not instantaneous). However, the aforementioned conservatism should not be interpreted as being applicable to any applied stress. In other words, this conservatism is only applicable to residual stress. Instantaneous stresses which are transient in nature, even if they are well in excess of the RST, will not result in crack initiation as they are not present for sufficient time to allow the requisite metal dissolution to take place.

1.2 TEMPORAL NATURE OF TRANSIENT STRESSES DUE TO ROCKFALL OR OTHER MECHANICAL IMPACTS TO THE WASTE PACKAGE

When a waste package impacts another waste package or a pallet during a seismic event, the loading path has three phases: (1) elastic loading until reaching the elastic yield limit; (2) plastic loading above the elastic yield limit; and (3) elastic unloading when the external load is removed, reducing the local stress. SAR Figure 2.3.4-57 illustrates this loading sequence, demonstrating that plastic deformation does not always generate a damaged area because the final residual stress state may be compressive or, if tensile, it may be below the threshold to initiate SCC.

The stresses during phases 1 and 2 may be in excess of the SCC RST presented in Section 1.1; however, these stresses are transient in nature. As the material plastically deforms, stress is relaxed and the remaining residual stress is far below the peak stress. This transient nature has been demonstrated via calculations presented in *Naval Long Waste Package Vertical Impact on Emplacement Pallet and Invert* (BSC 2007), in which its Figure 7-5 illustrates the time-dependent maximum stress (in this case, the Von Mises stress) for one of the loading cases evaluated. While the magnitude of the stresses varies from scenario to scenario, the time dependency illustrated in that figure is characteristic of all the impact cases documented in the reference. The impact presented in *Naval Long Waste Package Vertical Impact on Emplacement Pallet and Invert* (BSC 2007, Figure 7-5) was 15 ms in duration. While the peak stresses were achieved just prior to the end of the impact, the remaining effective stress had decayed by more than 50% after 5 ms, and was continuing to rapidly fall off with time. As such, it is clear that the transient stresses associated with the impact are far greater than the stress state which exists within the material almost instantaneously (5 ms) following the impact.

1.3 IMPACT OF TRANSIENT STRESSES ON SCC INITIATION AND CRACK GEOMETRY

SCC progresses through the interaction of a residual (or applied) stress and a corrosion process. Crack propagation is typically slow, owing to the kinetics of the corrosion process which is, in effect, the rate limiting process. Therefore, transient stresses which are present for less than one fiftieth of a second are not relevant to this process. In addition, the TSPA does not consider the impact of the environment or the absence/presence of potential crack nuclei on whether SCC will

take place. As such, processes which increase potential nucleation sites or provide an environment which might support metal dissolution have no impact on the treatment of SCC in the TSPA analysis. SCC occurs when the RST is exceeded within the material, regardless of whether or not crack nuclei or a corrosive environment is present.

If the residual stress is greater than the RST, SCC cracks form, and the length of SCC per unit area of the waste package (which has residual stress in excess of the threshold stress for SCC crack formation) is calculated by determining the effective maximum density of cracks which the residual stress level present can support. This effective maximum density is arrived at via calculations which determine the minimum spacing between two adjacent parallel stress corrosion cracks. This minimum spacing is based upon the fact that as a crack forms, the residual stress which drives the formation of the crack will be relieved, and as such, additional cracks would not be able to nucleate and grow within the region (SNL 2007, Section 6.7.2).

1.4 SUMMARY

Transient stresses will have no impact on the potential for, growth rate of, or resulting crack geometry for SCC, and as such, transient stresses are not considered by the TSPA in determining whether SCC can or cannot take place.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

ASM International 2003. ASM Handbook Vol. 13A: *Corrosion: Fundamentals, Testing, and Protection*, “Stress Corrosion Cracking,” pp. 346-366.

BSC (Bechtel SAIC Company) 2007. *Naval Long Waste Package Vertical Impact on Emplacement Pallet and Invert*. 000-00C-DNF0-00100-000-00C CACN 002. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071017.0001; ENG.20071116.0011; ENG.20080401.0004^a.

SNL (Sandia National Laboratories) 2007. *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials*. ANL-EBS-MD-000005 REV 04 ERD 2. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070913.0001; LLR.20080311.0084; LLR.20080408.0242.

NOTE: ^aProvided as an enclosure to letter from Williams to Sulima dtd 03/17/2009. “Yucca Mountain – Request for Additional Information – Volume 2, Chapter 2.1.1.7, 2nd Set (Department of Energy’s Safety Analysis Report Section 1.5.2) – Design of Systems, Structures, and Components Important to Safety and Safety Controls”

RAI: Volume 3, Chapter 2.2.1.3.1, Third Set, Number 5:

Provide additional technical basis for the assumption that the upper bound for the length of through-wall stress corrosion cracks in the seismically damaged area of the waste package is twice the thickness of the waste package wall.

Basis: For stress corrosion cracks in the seismically damaged area of the waste package, the upper bound for crack length is assumed to be twice the waste package thickness. DOE states that this is the same crack length that is used for radial cracks in the closure weld region in the nominal scenario (SNL, 2007, Section 6.7.3.2). The crack length in the nominal scenario, however, is limited by the attenuation of weld residual stresses normal to the weld-metal interface (SNL, 2007, Section 6.6.1). The size of the stress-field and the distribution of stress magnitude within that field may be much different in the seismically damaged waste package. Conceptual models for crack morphology not considered by DOE (e.g. multiple small cracks coalescing to form a large crack or cracks that span the entire damaged area) might give a crack length that is longer than that assumed in DOE's model abstraction. Cracks with sufficient length may provide a pathway for advective transport of radionuclides through the waste package wall if the opening width is such that precipitate plugging and crack tortuosity cannot prevent the flow of water through the cracks. The requested information is needed to verify compliance with 10 CFR 63.114(f).

1. RESPONSE

In calculating the total stress corrosion cracking (SCC) crack length in the seismic scenario, and hence the cross sectional area available for diffusive mass transport, the maximum density of cracks which could be supported by the residual stress present within a damaged portion of the waste package outer barrier has been conservatively estimated. The analysis then assumes that this density of cracks forms instantaneously in the entire damaged region of the waste package outer barrier whenever the residual stress exceeds the threshold stress for SCC crack initiation. While it is conceivable that there could be cracks longer than twice the waste package thickness (the size utilized in the analysis), this would result in a lower number density of cracks, as well as a smaller crack opening displacement for each crack. In fact, the analysis of the crack opening displacement for each crack is based upon the assumption that the residual stress present when the crack initiated is always present, even after the crack has propagated. Thus, while the stress (and hence, crack opening displacement) would in reality approach zero as cracks propagate through the material, the model conservatively assumes that this does not take place, and that a residual stress equal in magnitude to the yield strength of the material remains. As such, the approach utilized in the total system performance assessment (TSPA) provides a highly conservative estimate of the total SCC crack opening available for diffusive mass transport.

1.1 CRACK LENGTH AND DISTRIBUTION IN THE TSPA

The length of SCC cracks per unit area of the waste package (which has residual stress in excess of the threshold stress for SCC crack formation) is calculated by determining the effective

maximum density of cracks that the residual stress level present can support. This is arrived at via calculations that determined the minimum spacing between two adjacent parallel stress corrosion cracks. This minimum spacing between cracks is based upon the fact that, as a crack forms, the residual stress that drives the formation of the crack will be relieved, and as such, additional through-wall cracks would not be able to form within the region.

The minimum spacing between two parallel through-wall cracks in a plate or the wall of a large diameter cylinder such as the waste package is equal to the thickness of the plate, t . In determining the maximum number density of stress corrosion cracks per unit area, two scenarios were considered (SNL 2007, Section 6.7.3). In the first case, the cracks were arranged in parallel rows of parallel cracks in a hexagonal array, with the row spacing equal to the thickness of the plate, t (SNL 2007, Figure 6-62), and a crack length of $\left(\frac{2}{\sqrt{3}}\right)t$ (such that adjacent cracks did not overlap). In that case, the number density of cracks (ρ_{SCC}) was found to be $\frac{\sqrt{3}}{2t^2}$ in a damaged area. In the second case, parallel rows of parallel cracks of length $2t$ with centers arranged in a hexagonal array, with the length of each side of the hexagon equal to t (corresponding to a row spacing equal to $\left(\frac{\sqrt{3}}{2}\right)t$), which allows adjacent cracks to overlap (SNL 2007, Figure 6-64). In this case, ρ_{SCC} was found to be $\frac{2}{\sqrt{3}t^2}$. In both cases, the total length of cracks is equivalent to the patch size (area) multiplied by the crack density and then multiplied by the crack length, or 0.9 meters per 150 mm \times 150 mm patch for the first case, and 2.1 meters for the second. In both cases, (SNL 2007, Figure 6-62 and 6-64) each row of parallel cracks is in effect a single continuous crack.

If, as suggested in the RAI, a longer crack were to form, it would limit the growth of additional cracks in the same manner as the cracks considered in the analysis. In other words, a parallel through-wall crack would need to be at least a distance equal to the thickness of the plate away from that crack in order to propagate completely through the plate. As such, a longer through-wall crack would not necessarily result in an increased total length of through-wall SCC cracks within a particular patch.

1.2 CRACK OPENING AVAILABLE FOR MASS TRANSPORT

As discussed in *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials* (SNL 2007, Section 6.6.2), a through-wall stress corrosion crack is assumed to be semicircular in nature, with a depth of a , and a length of $2c$ where a is equal to c . The crack opening displacement, δ , for such a crack in an infinite sheet is defined as (Tada 2000, p. 125):

$$\delta = \frac{(4c)\sigma}{E}$$

where σ is the stress and E is the Modulus of Elasticity.

The cross-sectional area of the elliptical opening for a single crack can then be estimated as (SNL 2007, Equation 31):

$$A_{cr} = \frac{\pi}{4} \delta (2c) = \frac{(2\pi c^2) \sigma}{E}$$

For a semicircular, through-wall crack, c is equal to the thickness of the plate, t .

The total area of stress corrosion cracks per unit area of the waste package outer barrier in regions where the stress exceeds the threshold stress for SCC initiation is equal to the product of the area for an individual crack and the number density of cracks. In the first case (a hexagonal array of parallel cracks with the row spacing equal to the thickness of the plate, t , and a crack length of $\left(\frac{2}{\sqrt{3}}\right)t$ as described above in Section 1.1):

$$SCC \text{ Area Density} = A_{cr} \rho_{SCC} = \left(\frac{\sqrt{3}}{2t^2} \right) \left(\frac{(2\pi t^2) \sigma}{3E} \right) = 1.81 \frac{\sigma}{E}$$

And for the second case (a hexagonal array of parallel cracks with the row spacing of $\left(\frac{\sqrt{3}}{2}\right)t$, and a crack length of $2t$, as described above in Section 1.1):

$$SCC \text{ Area Density} = A_{cr} \rho_{SCC} = \left(\frac{2}{\sqrt{3}t^2} \right) \left(\frac{(2\pi t^2) \sigma}{E} \right) = 7.26 \frac{\sigma}{E}$$

In the TSPA, these two cases are used to establish bounds on the through-wall SCC areal density, and the value used in the analysis is sampled from a normal distribution between the two cases defined above (SNL 2007, Section 6.7.3.3). The stress used to calculate this area is the same stress that caused the cracks to form—in other words, when calculating the crack opening, the analysis assumes that the stress acting to open the crack is the same stress that resulted in its formation.

As an SCC crack propagates, the residual stress within the material will be relieved. Thus, the assumption that a stress equivalent to the yield strength of the material will remain, even after the crack has propagated, is highly conservative. In other words, while the stress (and hence, crack opening displacement) would in reality approach zero as SCC cracks propagate through the material, it is conservatively assumed in the model that this does not take place, and that the stress remains at a level equivalent to the yield strength of the material. As such, the approach utilized in the TSPA provides a highly conservative estimate of the total SCC crack opening available for diffusive mass transport.

While other crack geometries, could be considered, they are not expected to result in significant crack opening displacement due to the relief of residual stress as the crack advances. These tight

cracks, irrespective of their length, would be plugged by agglomerated mineral precipitates and corrosion products, thereby limiting the amount of water inside the cracks and the potential for advective water flow (SNL 2008, FEP 2.1.03.10.0A, p. 6-456; see response to RAI: 3.2.2.1.2.1-2-002). This same statement would hold for cracks assumed to form by the analysis.

1.3 SUMMARY

The SCC crack density assumed to be present in the analysis represents the maximum through-wall crack density that can exist in a plate of a given thickness. While the cracks were limited to twice the waste package thickness, in effect each series of parallel cracks is in effect a single continuous crack. The analysis then assumes a residual stress equivalent to the yield strength of the material will always be present in damaged regions, even after crack propagation has taken place—in other words, stress relaxation is ignored. As a result, the analysis used in the TSPA for the area available for diffusive mass transport through the waste package outer barrier is highly conservative. While a longer crack could be considered in the analysis, such cracks would not necessarily result in an increased total length of through-wall SCC cracks present within a damaged region of the waste package outer barrier. Furthermore, such cracks would be tight due to the relaxation of residual stress within the material as the crack progresses. The analysis conservatively ignores this latter effect in determining the area available for diffusive mass transport, and as such, conservatively over-predicts the effect of any through-wall crack density, total length, or geometry.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

SNL (Sandia National Laboratories) 2007. *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials*. ANL-EBS-MD-000005 REV 04 ERD 2. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070913.0001; LLR.20080311.0084; LLR.20080408.0242.

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